Seismic Source Characterization for Dam Site Analysis in California

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Introduction

Today I will discuss the Division's method of characterizing active faults and determining design earthquake parameters for the analysis of a dam site. Since the group is largely state dam safety officials, I would like to start by briefly discussing the role of the Geology Branch within the California dam safety organization.

Role of Geology Branch

The Division's Geology Branch includes a staff of 4 engineering geologists, who support both the Design Engineering Branch and the Field Engineering Branch. In addition to developing design earthquake parameters for the analyses of dams, we assist Design Engineering Branch by monitoring site exploration at proposed sites and dams undergoing reanalysis. Based on the exploration, we provide a description of the geologic characteristics of the site and materials, identify foundation defects which affect design, and identify special geologic conditions which require additional investigation.

After the investigation phase, we participate in the review of the design proposal. We evaluate the adequacy of the foundation for the type of dam proposed and assist in developing a functional objective for foundation stripping. We comment on foundation treatment, grouting requirements, and drainage requirements. We identify conditions or problems which will require special attention during construction and comment on construction materials in terms of quality and quantity.

We notify Field Engineering Branch staff of earthquake events in California. Notification is on a 24-hour basis for earthquakes greater than magnitude 5, and on a next working day basis for earthquakes between magnitude 4 and 4.9.

We assist Field Engineering Branch construction inspection staff by advising if the foundation objective has been achieved, documenting the geology of the foundation exposure, and investigating any construction problems such as landsliding. Finally, we assist maintenance inspection staff by participating in the investigation of geologic-related problems occurring during the operational life of the more than 1200 jurisdictional dams.

Development of Design Earthquake Parameters

I would now like to discuss the method by which Geology Branch develops design earthquake parameters. During the course of this discussion, I will formally introduce two recently developed policies: a major revision to our fault activity guidelines, and minimum design earthquake parameters.

The Geology Branch uses the traditional deterministic approach to seismic hazard analysis to develop design earthquake parameters. Our approach is summarized on the flow chart included as Figure 1. The faults within the proximity of the site are identified and assessed for activity. A maximum earthquake scenario is specified, based on the maximum magnitude for that fault at the closest distance with respect to the site, for each active or conditionally active seismic source. A representation of the site condition is chosen. Peak ground acceleration, bracketed duration, and predominant period are calculated for each maximum earthquake scenario. Several significant events are reported to the engineering staff providing alternative events for the analysis of the dam.

We routinely provide design earthquake parameters during the design review phase of each proposed jurisdictional dam. This process usually involves reviewing the basic geologic information and proposed parameters submitted by the owner's engineer. Geology Branch staff reviews the submitted material, but always performs an independent determination of the design earthquake parameters. We also reevaluate previously developed parameters if an existing dam is to be re-analyzed. In some cases a stability-related problem triggers a reevaluation of the earthquake parameters.

I would like to emphasize that the deterministic seismic hazard analysis is time independent. The specified event is possible, but there is no consideration of the likelihood of occurrence within the life of the dam. A probabilistic seismic hazard analysis considers event likelihood and the uncertainty of the ground motion estimate. Jeff Howard of the Geology Branch staff will compare deterministic and probabilistic seismic hazard analyses as they relate to dams.

Identify Faults

Faults in the proximity of the site are compiled by several means. The first step is to perform a literature search, reviewing all available geologic reports and maps. Initial site exploration should include an evaluation of aerial photographs and satellite imagery, to identify lineaments and other suggestions of faulting. Historic aerial photographs, taken prior to large scale development, are especially useful in California for recognizing landforms created by faulting. After the photo reconnaissance, detailed geologic mapping of the damsite should be performed. The mapping should investigate any lineaments identified by the photo reconnaissance as well as all geologic contact relationships. Trenching is often necessary to provide subsurface exposures across lineaments and to investigate contact relationships.

Determine Active Seismic Sources

After all faults and suspected faults are compiled, the active seismic sources are identified. This step is fundamental to the deterministic method and is perhaps the most significant portion of the analysis. All sources judged to be inactive are eliminated from the analysis, and only those seismic sources judged to be active or conditionally active will be considered further.

The presence of seismicity may confirms the presence of an active fault. However, the San Andreas fault north of San Francisco, which ruptured in 1906, is currently experiencing almost no seismicity. This very dramatically illustrates the limitations of historical seismicity as an absolute indicator of fault inactivity.

Unlike many areas of the U.S., where the seismic sources are poorly expressed at the surface, California has many faults which cut the surface. This allows identification and detailed investigation, including direct measurement of physical properties, such as fault length and displacement. Because the seismic hazard in California has long been recognized, we are fortunate to have substantial compilations of basic data such as the Fault Activity Map of California (Reference 1).

The active tectonics of California is a topic that stands by itself. I am pleased to announce that we have Dr. Clarence Allen to provide an overview of California Faults and their Seismic Hazard.

Information on fault recency is one of the most useful items which have been compiled on the State fault map. Each fault is identified according to the age of the youngest known geologic unit it offsets, expressed in terms of geologic epochs or periods. I will review the geologic epochs and periods significant to this discussion. Shown on the State fault map are: faults which have ruptured Holocene age materials (within last 10,000 years), faults which have ruptured Late Quaternary age materials (between 10,000 and 700,000 years), faults which have ruptured Quaternary age materials (between 700,000 and 1.6 million years), and faults which have ruptured only pre-Quaternary age materials (older than 1.6 million years). Note that the Holocene epoch and Pleistocene epoch collectively make up the Quaternary period.

You may have noted that some of the recency categories are well beyond the range usually considered for fault activity determinations. The age of the youngest known offset is the maximum age of a fault; that is, the fault has moved since the deposition of that unit. The movement could be younger, and in some cases significantly younger, than the age of the offset unit. For example, a fault which ruptures Late Quaternary materials has moved sometime during the last 700,000 years, but that last movement could have been only few hundred years ago. Additional refinements of the age are possible only if younger materials are available to record the evidence of the most recent movements.

The oldest geologic unit not offset by a fault is an indicator of a fault's minimum age; that is, the confirmed time since the last movement. Subsurface exploration is often required to determine the minimum age. The goal of such exploration is dating units which have and have not been offset by the fault, thereby obtaining a chronology of the fault's recent behavior. We are fortunate to have with us Dr. William Lettis of William Lettis and Associates who will discuss Active Fault Recognition and Paleoseismic Investigation Techniques.

Fault Activity Guidelines

Several years ago the Division's Consulting Board for Earthquake Analysis recommended that we review our active fault criteria. Previously, the Division considered displacement during the Holocene as the definition of an active fault, and displacement during the Pleistocene, or a judgment that a fault played a role in the current tectonic regime, as the definition of a potentially active fault. There was no formal definition for an inactive fault, nor was there a statement as to the design implications of the two activity categories.

We have substantially revised the criteria, and I will formally present the new guidelines today. The goal of these guidelines is to provide consistent determinations of fault activity by Geology Branch staff, to provide an understanding of the design implications of the determination, as well as to provide clear direction to dam owners investigating seismic sources significant to their dams. A copy of the guidelines is included as Figure 2.

We define three general categories of seismic sources: active, inactive and conditionally active.

Active Seismic Sources

We presently define an active seismic source as a fault which has experienced at least one displacement event within the last 35,000 years. The 35,000 year value was selected based on our belief that Holocene activity was not a sufficiently conservative criteria for elimination of a fault as a seismic source in the analysis of a dam. We looked at several other potential specifications, including 100,000 years, both in terms of the level of conservatism and if faults of that age would be recognizable.

The 35,000 year specification essentially defines a level of risk. A fault which has not moved in the last 35,000 years can be thought of as having an recurrence interval of greater than 35,000 years, and we have made the judgment that the chances of a future event are sufficiently unlikely. However, there may be no physical reason why a fault, which has not moved within the last 35,000 years, could not move again. Faults exhibit a wide range of average recurrence intervals, from a few tens of years to over several hundred thousand years.

Two sub-categories of active seismic sources are defined: the Holocene active fault, and a new term, the Latest Pleistocene active fault. The categories are distinguished for descriptive purpose; however, as our Board has encouraged us to consider, these sub-categories could conceivably define separate activity criteria applicable to dams of different type or risk category.

The guidelines give examples of the lines of evidence which demonstrate a fault as Holocene or Latest Pleistocene active. Stratigraphic displacement of Holocene age materials is one way a Holocene active fault is identified. Holocene active faults are compiled on the Fault Activity Map of California. Some of this data is obtained through the California Division of Mines and Geology's Alquist Priolo Special Studies Zone program. Under this program, especially well-defined Holocene active faults are identified by Division of Mines staff; furthermore, some property owners within the fault zone are required to perform subsurface investigations to locate individual fault traces for setback requirements.

Geomorphic evidence of Holocene displacement or tectonism is another way that a Holocene active fault is identified. Repeated Holocene displacement usually results in strong geomorphic expression in the landscape, including landforms such as offset stream courses, linear valleys and scarps, and sag ponds. Tectonism is defined as crustal deformations which are indicative of faulting, such as the folding of youthful materials overlying an active blind thrust fault.

Other lines of evidence of Holocene activity include geodetically measured tectonism, observations of fault creep, and well-located zones of seismicity.

Latest Pleistocene active faulting is not as well documented in the literature as Holocene activity and, generally speaking, materials of this age are more difficult to recognize. The lines of evidence which demonstrate faulting of this age include stratigraphic or geomorphic evidence of displacement to 35,000-year-old materials. Age dating of geologic materials within this time frame is possible using radiocarbon and soil stratigraphic techniques. Bill Lettis will discuss the practical aspects of recognizing Latest Pleistocene faulting events in more detail.

Inactive Seismic Sources

Perhaps the most important aspect of the guidelines is the criteria by which a fault can be shown to be an inactive seismic source.

Generally speaking, inactivity is either demonstrated or presumed. Inactivity can be demonstrated by a confidently located fault trace which is consistently overlain by unbroken geologic materials 35,000 years or older, or other observation indicating lack of displacement within 35,000 years. Faults which have no suggestion of Quaternary activity are presumed to be inactive. The presumption of inactivity is made if both of the following conditions are met: there needs to be no evidence of displacement to Quaternary age materials, <u>and</u> Geology Branch staff must believe the fault has no attributes consistent with the current tectonic regime.

Conditionally Active Seismic Sources

The revised guidelines establish criteria as to the need to investigate faults which are potentially significant to an analysis, but have incomplete or inconclusive evidence of activity. The conditionally active seismic source has been developed to describe seismic sources which will be treated as an active seismic source for the purposes of design or reevaluation, with the understanding that additional investigation or analysis could change that designation. The often misused term Potentially Active fault has been completely dropped.

A Conditionally Active fault meets one of the following two criteria:

1. A Quaternary active fault with a displacement history during the last 35,000 years, which is not known with sufficient certainty to consider the fault either an active or inactive seismic source. (Demonstrated Quaternary activity is a common investigative threshold for a potentially

significant fault. Because faults which displace Quaternary age materials are well-documented on the State Fault Activity Map, we believe the guideline is practical as well.)

2. A pre-Quaternary fault which can be reasonably shown by Geology Branch staff to have attributes consistent with the current tectonic regime. (This approach is sometimes used in areas of older rocks, such as metamorphic and granitic terrain.)

A specific example of a pre-Quaternary fault, with attributes consistent with the current tectonic regime, is given on the guidelines. During the last 5 million years the Sierra Nevada Mountains, which are east of Sacramento, have been uplifted thousands of feet. Relatively vigorous faulting associated with the uplift continues today along the eastern escarpment of the range. In the western foothills of the range, moderate magnitude seismicity and relatively small stratigraphic displacements are occurring along reactivated portions of an ancient fault system in response to the uplift.

Quaternary activity is not readily recognizable due to the sparse Quaternary-age cover in the foothill region. Therefore, demonstrated Quaternary activity is not a particularly useful or conservative threshold for defining conditional activity. In this case, the Division considers major ancient fault traces to be conditionally active, based on the reasoning that these faults are the primary zones of weakness in the region and therefore the likely sites of reactivation. There are numerous dams in the Foothill region including some of the State's largest; therefore, investigations have been conducted which have shown portions of the system to be active and inactive.

Slip Rate and Recurrence Estimates

Geology Branch staff report available information on slip rate and recurrence intervals for all active seismic sources (which include conditionally active seismic sources, which are treated as active seismic sources for the remainder of the analysis).

The slip rate, commonly expressed in mm/year, is the average rate of displacement which is occurring along a fault during a specified time period, such as the Holocene. The recurrence interval is the average number of years between large events. This information is not used in the deterministic approach, but we report this information for descriptive purposes.

We find it helpful to discuss slip rate within the context of the roughly 50 mm/year of slip which is occurring between the North American and Pacific plates. This provides some measure as to the relative importance of a given fault in the current tectonic regime. Consider the contrast in slip rate between the San Andreas fault system at 35 mm/year, which is relieving about 70% of the total slip between the plates, and the segments of the Foothill fault system at 0.05 mm/year, which are relieving 0.1% of the total slip between the plates.

Maximum Magnitude Determination

A maximum magnitude is determined by Geology Branch for each active seismic source. The maximum magnitude (also referred to as the MCE or Maximum Credible Earthquake) is the largest event capable of occurring along a fault. It is determined without consideration to frequency of occurrence.

Several approaches to magnitude determination have evolved. The Geology Branch uses all appropriate approaches, but I'll discuss our most commonly used approach: an estimation of magnitude from physical fault parameters, such as surface rupture length.

Segmentation

Most faults expressed at the surface have resulted from repeated displacement events, which have occurred on contiguous or overlapping rupture segments. This is well illustrated by the historic events on the North Anatolian fault zone in Turkey, where 10 contiguous or overlapping rupture events have occurred between 1939 and 1967.

Relationships between magnitude and resulting physical fault parameters, such as surface rupture length, have been developed based on seismologic and field measurements from hundreds of historic earthquakes. If one can deduce the surface rupture length associated with past large earthquakes, the magnitude of those events can be estimated using this relationship, leading to a maximum magnitude estimation.

Deduction of the surface rupture length associated with past earthquakes involves dividing the fault into individual segments which are thought to represent the rupture of a past event. The well-defined segments of the Beaverhead fault in eastern Idaho provides a good example. The Baldy Mountain segment is separated from the Nicholia segment by a prominent barrier, measured on the order of square kilometers. Barriers are strong areas along the fault which can stop a propagating rupture and can be used to define the end points of a segment thought to rupture in a single event.

It is too simplistic to believe that even prominent barriers will not eventually be broken. It is usually necessary to consider the possibility that more than one segment will rupture in a large event. An excellent example of this approach is the seismic characterization of the southern San Andreas fault for Eastside Reservoir. Ebasco, the design consultant to Metropolitan Water

District, developed a number of segment rupture scenarios involving as many as six segments of the fault (Reference 2).

As the number of segments increase, the total rupture length increases, and the magnitude of the responsible earthquake increases. Ebasco's magnitude estimates for events on the southern San Andreas fault range from magnitude 7.0 for a single segment event, to magnitude 7.9 for a six segment event. The maximum magnitude ultimately used for characterizing the southern San Andreas fault was moment magnitude 8. The maximum magnitude selected is slightly larger than the postulated six segment scenario, and considerably longer than the rupture of the 1857 earthquake, the largest historic event on this portion of the fault.

As rational as this approach is, the unexpected can happen. During the 1992 Landers earthquake, a northerly propagating rupture jumped between four separately mapped northwest trending faults. This rupture scenario, although not unprecedented, probably would not have been predicted prior to its occurrence.

Distance Determination

Geology Branch develops earthquake ground motion parameters assuming the closest distance between the seismic source and the dam site. A rigorous analysis of measurement techniques shows five possible distances which could be considered:

1. hypocentral distance (site to point of origin of rupture)
2. epicentral distance (site to surface location above hypocenter)
3. site to the high stress zone along the fault plane
4. site to closest portion of the fault plane
5. site to surface trace of the fault

It is not necessarily overly conservative to assume the closest distance between the site and fault plane in developing design earthquake parameters, especially for the larger magnitude events. The zones of high stress, along a fault plane, are most closely associated with highest ground motions, but their locations cannot be predicted in advance. Large magnitude events involve longer portions of the fault and presumably have larger and more frequent zones of high stress.

The epicentral and hypocentral distances are the least significant distance measurement. To illustrate the lack of association between the epicenter and the highest ground motion, consider that during the 1992 Landers Earthquake the largest displacements and highest peak accelerations occurred

40 kilometers north of the epicenter, where the northerly propagating rupture encountered a second large high stress zone.

Site Condition Determination

Geology Branch develops recommendations for describing the site conditions in terms significant to earthquake parameters. The engineer usually elects to perform a one-dimensional response analysis, where bedrock ground motions are attenuated from the bedrock interface through a site specific soil model up to the dam. On occasion, however, a peak acceleration for a soil site is estimated from empirical data.

Using an empirical approach, the damsite can be characterized as one of the four site conditions which influence peak acceleration and spectral content of the ground motion. These site conditions are: rock, stiff soil up to 200 feet in depth, cohesionless soils greater than 250 feet deep, and soft to medium stiff clays and sands.

Peak Bedrock Acceleration, Bracketed Duration, and Predominant Period Determination

The Geology Branch determines design earthquake parameters, which include peak horizontal bedrock acceleration, bracketed duration, and predominant period. Peak horizontal bedrock acceleration is determined using a working interpolation of the Seed and Idriss (1982) attenuation relationship (Reference 3). The Division determines bracketed duration - the duration of shaking above 0.05g - using a working interpolation of the relationship by Bolt (Reference 4). Predominant period - the period of vibration in which the largest spectral acceleration is attained - is determined using a working interpolation of the relationship of Seed, Idriss, and Kiefer (Reference 5).

Reporting of Significant Events

Staff provides a written discussion of the age of faulting, the activity determination, the slip rate, the recurrence interval, and the rational for a new or revised maximum magnitude determination for each active seismic source.

Usually, the seismic source with the highest peak horizontal bedrock acceleration is the most significant event for the analysis. Sometimes seismic sources which yield lower accelerations but have longer duration or more critical predominant period are equally or more significant. Geology Branch reports at least three significant events to the Design Engineering Branch, which in turn selects the controlling event to be used in the analysis. In a table format, Geology Branch staff reports the distance, the maximum magnitude, peak bedrock acceleration, bracketed duration, and predominant period for each significant source.

Minimum Earthquake Policy

Finally, I would like to discuss our new Minimum Earthquake policy. The Division now requires all new jurisdictional dams, and dams undergoing major rehabilitation, to be designed to minimum design parameters. This policy has been developed in response to recent California earthquakes which have occurred on previously unrecognized seismic sources.

The dams subject to this policy will be designed to withstand not less than a peak horizontal bedrock acceleration of 0.20g. Although this Minimum Earthquake is specified in terms of ground motion, it approximates an event of magnitude 6-1/2, at a distance of 8 miles, with a bracketed duration of 18 seconds.

A target response spectrum envelope has been developed for the horizontal motion at a rock site (Figure 3). The envelope defines the mean and mean +1 spectral accelerations for the Minimum Earthquake event, developed using the average of three recent attenuation relationships, which directly consider the influence of earthquake magnitude, distance, and site conditions on spectral shape.

The Minimum Earthquake will be used when it produces more severe ground motion than the site-specific estimates. The Minimum Earthquake is most applicable in the Great Valley, the western slope of the Sierra Nevada, the southeast desert region, and the northern-most portion of the State.

References

1. Jennings, Charles W., 1994, Fault Activity Map of California and Adjacent Areas, California Division of Mines and Geology, Geologic Data Map No. 6.

2. Metropolitan Water District, Domenigoni Valley Reservoir, Appendix A, Regional Seismic Source Characterization for Deterministic Ground Motion Evaluation, August 1994.

3. Seed, H.B., and Idriss, I.M., 1982, Ground motion and Soil Liquefaction during Earthquakes, Monograph No. 5, Earthquake Engineering Research Institute.

4. Bolt, B. A., 1973, Duration of Strong Ground Motion, Proceedings of the Fifth World Conference on Earthquake Engineering, Paper 292, Rome.

5. Seed, H.B., Idriss, I.M., and Kiefer, F.W., 1969, Characteristics of Rock Motions during Earthquakes, Journal of Soil Mechanics and Foundation Division, American Society of Civil Engineers, pp. 1199-1218.

Deterministic Seismic Hazard Analysis

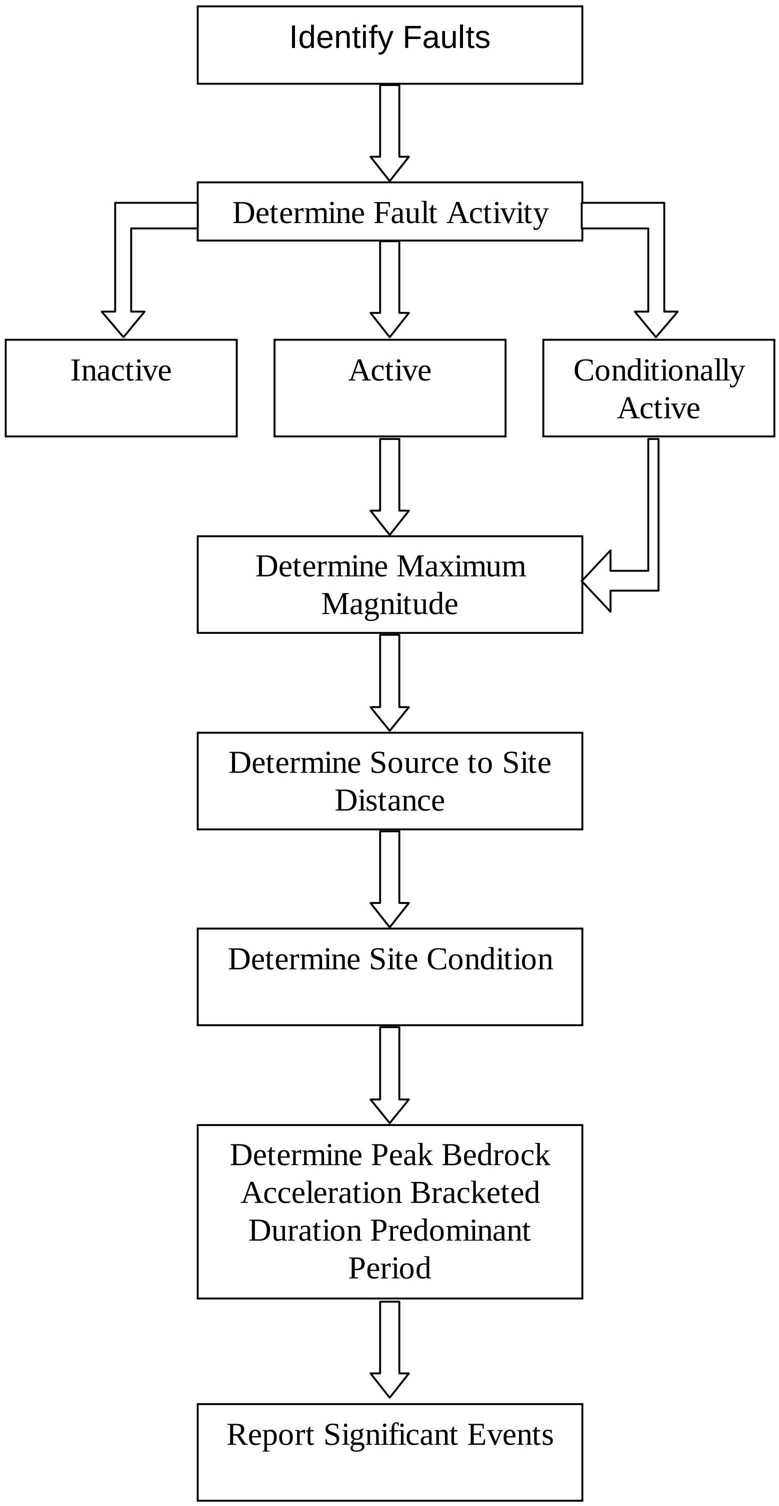


Figure 1

DSOD Fault Activity Guidelines

for use in deterministic fault activity assessments

Active Seismic Sources (considered seismic sources for dam design or reevaluation)

Holocene Active Fault: is a fault on which surface or subsurface displacement has occurred within the Holocene epoch. Holocene activity is demonstrated by one or more lines of evidence including the following:

Holocene (last 10,000 years) stratigraphic displacement.
Geomorphic evidence of Holocene displacement or tectonism[1].
Geodetically measured tectonism or observations of fault creep.
Well-located zones of seismicity

Latest Pleistocene Active Fault: is a fault on which no evidence of Holocene displacement is known, but which has experienced surface or subsurface displacement within the last 35,000 years. Latest Pleistocene activity is demonstrated by one or more of the following lines of evidence:

Stratigraphic displacement to units 11,000 to 35,000 years.
Geomorphic evidence of Latest Pleistocene displacement or tectonism.

[1]tectonism refers to crustal deformations which are indicative of faulting

Conditionally Active Seismic Sources (treated as a seismic source for dam design or reevaluation because of incomplete or inconclusive evidence, with the understanding that additional investigation or analysis could change the designation)

Conditionally Active Fault: a fault which meets one of the following criteria.

A Quaternary active fault (one that has experienced surface or subsurface displacement within the last 1.6 million years) with a displacement history during the last 35,000 years that is not known with sufficient certainty to consider the fault an active or inactive seismic source.

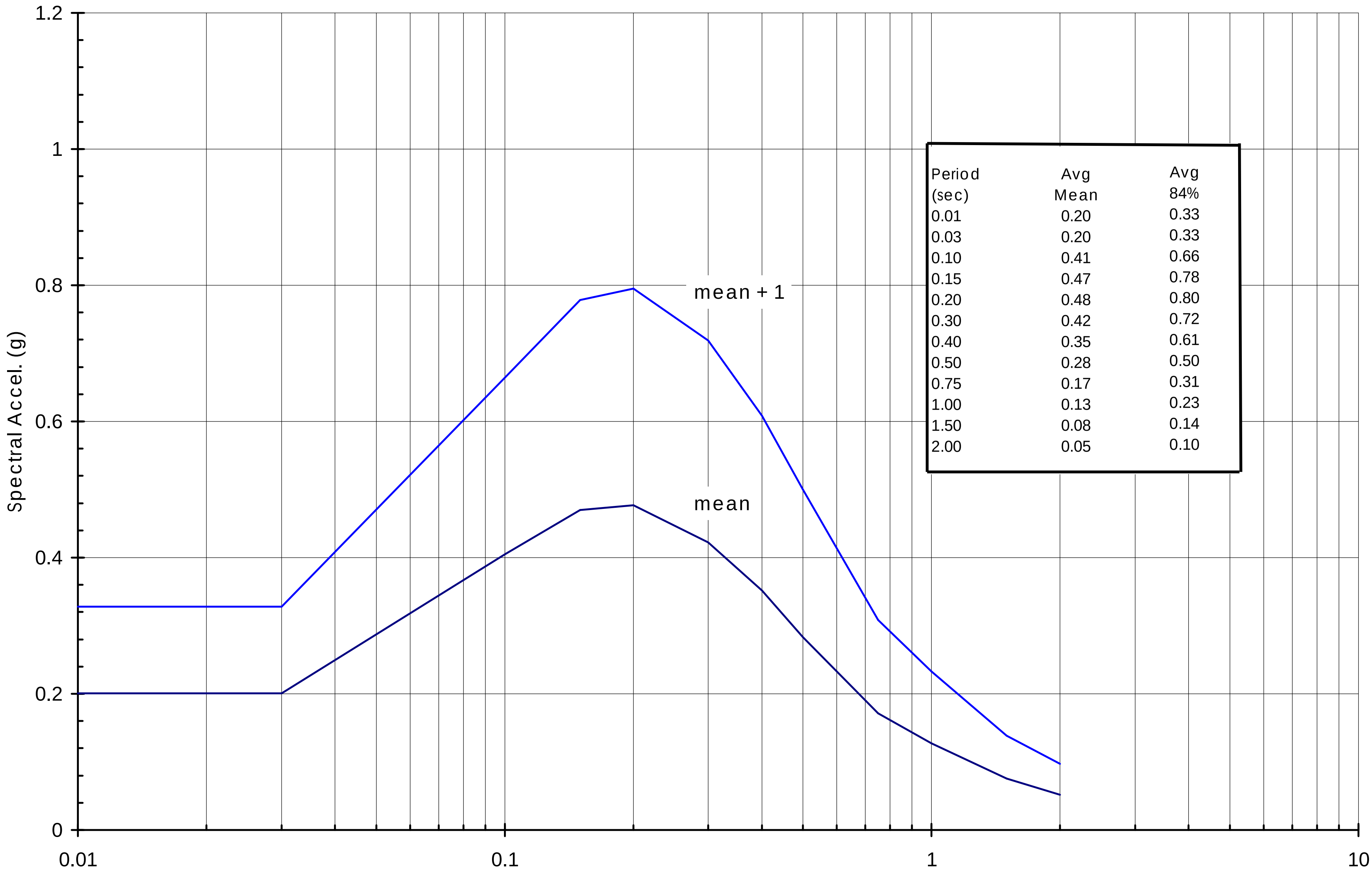
A pre-Quaternary fault which can be reasonably shown to have attributes consistent with the current tectonic regime. *Example...* In the foothills of the Sierra Nevada geomorphic province Mesozoic faults are considered Conditionally Active Seismic Sources unless proven otherwise.

Inactive Seismic Sources (not considered for dam design or reevaluation)

Inactive Fault: a fault which has had no surface or subsurface displacement within the last 35,000 years. Inactivity is demonstrated by a confidently-located fault trace which is consistently overlain by unbroken geologic materials 35,000 years or older, or other observation indicating lack of displacement. Faults that have no suggestion of Quaternary activity are presumed to be inactive.

Figure 2

Minimum Earthquake - Target Response Spectrum Envelope
5% Damping, M6-1/2, Rock Sites: after Idriss (1993), Geomatrix (1991), and Boore et al. (1993)



Period (sec)	Avg Mean	Avg 84%
0.01	0.20	0.33
0.03	0.20	0.33
0.10	0.41	0.66
0.15	0.47	0.78
0.20	0.48	0.80
0.30	0.42	0.72
0.40	0.35	0.61
0.50	0.28	0.50
0.75	0.17	0.31
1.00	0.13	0.23
1.50	0.08	0.14
2.00	0.05	0.10

Figure 3